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BORA ON THE NORTHERN ADRIATIC, 12-18 APRIL 1982

Bura na sjevernom Jadranu, 12-18. travanj 1982

VIŠNJA VUČETIĆ
Hydrometeorological Institute of Croatia, Zagreb, Yugoslavia
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Abstract: Analysis is presented of a bora case on 12-18 April 1982, characterized by the longest bora duration in Senj (138 hours) during the ALPEX-SOP. The bora was observed only on the northern Adriatic. The vertical wind and stability profiles indicate that the part of the upstream inversion layer decoupled and descended toward the sea which is confirmed in the aircraft data analysis (Smith, 1987). The application of the generalized hydraulic theory on the continuously stratified atmosphere showed that the theory can successfully explain the bora phenomenon in the postfrontal bora situation.

Key words: bora, generalized hydraulic theory

Sažetak: Prikazana je analiza situacije s burom od 12. do 18. travnja 1982. čija je karakteristika bila najdulje trajanje u Senju (138 sati) za vrijeme ALPEX-SOP. Bura je opažena samo na sjevernom Jadranu. Vertikalni profili vjetra i stabilnosti ukazuju na to da se dio navjetrinske inverzije razdvaja i spušta prema moru što potvrđuje analiza avionskih podataka (Smith, 1987). Primjena generalizirane hidrauličke teorije na kontinuirano stratificiranu atmosferu pokazala je da teorija može uspješno objasniti fenomen bure u postfrontalnim situacijama.

Ključne riječi: bura, generalizirana hidraulička teorija

1. INTRODUCTION

One of the most known local winds along the Adriatic Coast is the bora, the mechanism of which has not been thoroughly investigated. Many authors have examined the bora phenomena from various points of view and compared it with other similar local winds (Yoshino 1976, Reed 1981). Major progress for investigation of bora conditions has been particularly advanced by Smith after the Alpine Experiment (ALPEX). The availability of ALPEX research aircraft (Smith, 1982, 1984, 1987) and radiosounding data (Jurčec 1984, 1988, Vučetić 1984, 1985, 1987) made the observations of the bora vertical structure possible.

The intention of this paper is to present the basic characteristics of a strong bora case on 12 - 18 April 1982 during the ALPEX SOP and to examine the application of the hydraulic theory for bora maintenance in the analysed case.

A few days earlier (9 April 1982) a NE cold air outbreak over the northern part of Croatia caused a brief bora on the northern Adriatic (see Jurčec, in this Volume). A maximum increase in wind speed was registered in Senj (12.7 $ms^{-1}/2$ hrs) where the bora blew only 49 hrs. The considered situation with the NE cold air outbreak on 9 April 1982 was the strongest for that month in the ten-year period 1973 - 1982 (Bajić, 1984). The continuous cold air supply following this outbreak caused April 1982 to be the coldest in the period 1951 - 1980. For this situation Chen and Smith (1987) concluded that the low-level flow was blocked in a region north of the Alps and the large acceleration near the Adriatic was associated with the bora. The next case on 13 April had no significant synoptic-scale interference in the pressure field but the signal of the airflow blocked by the Alps was clearer in the trajectory analysis. This bora case (12-18 April 1982) could be classified as postfrontal bora and was characterized by the longest duration among all other ALPEX SOP boras (138 hrs in Senj). A maximum gust of 44 m s^{-1} was observed on 14 April on Tito's Bridge connecting Krk Island to the coast, with a maximum mean hourly wind speed of 25.2 m s^{-1}.

2. THE SYNOPTIC SITUATIONS AND MESOSCALE BORA CHARACTERISTICS

The cold air broke in the Adriatic Sea in an airstream around the easthern Alps causing a mesocyclone to form in the middle Adriatic on 14 April (Fig. 1). The maximum gusts were reached on Krk Island. The next day this mesocyclone filled up and an anticyclone over western Europe intensified. A trough of large amplitude and small wavelength at AT 500 hPa was over southern France which resulted in a cut-off low. Above our area there was a prevailing southerly wind. A large surface pressure gradient appeared across the Alps (Fig. 1). An unusually strong pressure difference between the Adriatic Coast and the continental part was observed (8 hPa, Fig. 2). The bora wind blew to the north of Split and on the southern Adriatic there was a prevailing scirroco (SE) at a speed of about 15 knots. Thus we only

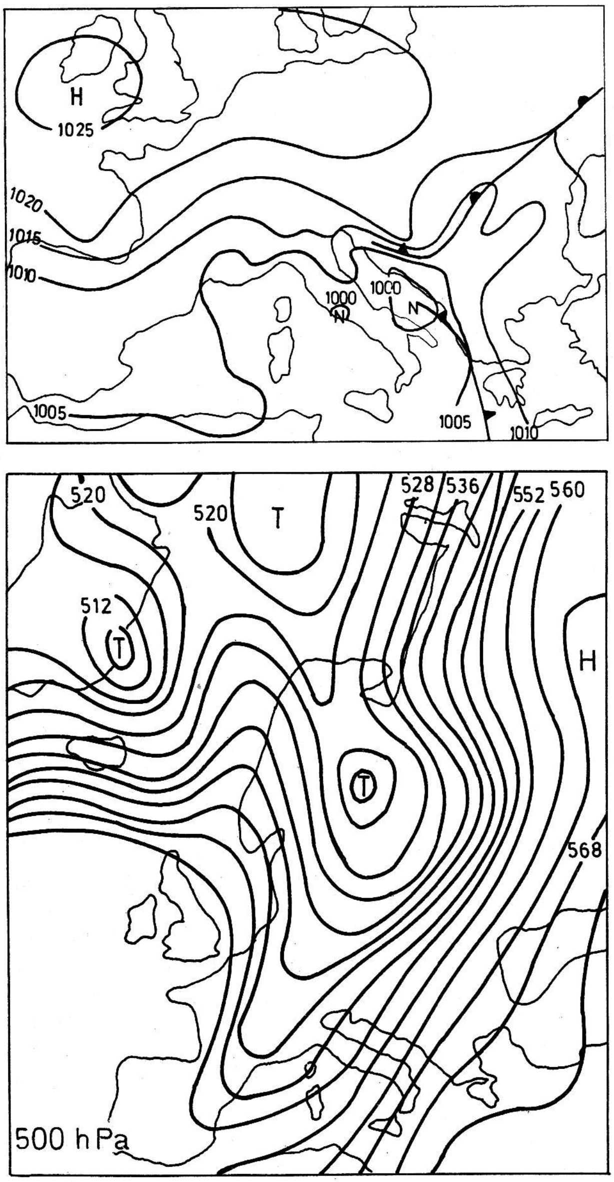


Fig. 1. Surface synoptic situation on 14 April 1982 at 12 GMT over Europe (above) and AT 500 hPa at 00 GMT (below)

Sl. 1. Prizemna sinoptička situacija za 14. 4. 1982. u 12 GMT iznad Evrope (gore) i AT 500 hPa u OO GMT (dolje)

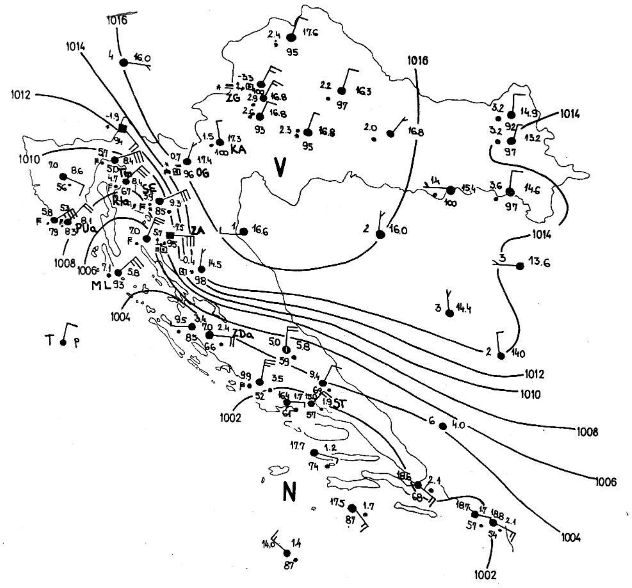


Fig. 2. Mesoscale analysis on the western of Yugoslavia on 14 April 1982 at 13 GMT. Solid lines are isobars. Wind (knots), temperature (°C) and sea level pressure (hPa) are plotted. Capital letters indicate the following stations: Zagreb (ZG), Karlovac (KA), Ogulin (OG), Zavižan (ZA), Senj (SE), Pula-airport (PUla), Titov most (Tito's Bridge - Tm), Rijeka-airport (Rla), Mali Lošinj (ML), Zadar-airport (ZDa) and Split (ST)

Sl. 2. Mezoanaliza zapadnog dijela Jugoslavije za 14. 4. 1982 u 13 GMT. Pune linije su izobare. Vjetar (čvorovi), temperatura (°C) i reducirani tlak zraka (hPa). Kratice označavaju slijedeće stanice: Zagreb (ZG), Karlovac (KA), Ogulin (OG), Zavižan (ZA), Senj (SE), Pula-aerodrom (PUa), Titov most (Tm), Rijeka-aerodrom (Rla), Mali Lošinj (ML), Zadar-aerodrom (ZDa) i Split (ST).

investigated the bora structure on the northern Adriatic Sea in more details.

The largest amount of precipitation in this situation was in Ogulin (windward side, Fig. 6) and in Senj (lee side, Table 1, Fig. 8). The precipitation amount of 42 mm was measured in Senj only on 14 April. During the strongest bora, however the rain intensity was lower (0.6 mm/hr) than during the earlier hours (5 mm/hr). This example shows that although rainfall may appear during the bora condition it is unlikely that it would have large intensity during maximum wind.

Inspite of the fact that in the majority of cases the strongest bora occurs in Senj, it is shown that in some situations the maximum bora gusts could be greater on some other locations. It is seen that the bora was stronger on Krk Island (Rijeka-airport 31.4 m s^{-1}) than at Senj (28.4 m^{-1}, Fig. 3). Concerning the maximum wind

Table 1. Total precipitation amount (mm) during a bora on 12-18 April 1982 for selected stations in Croatia

Tabela 1. Ukupna količina oborine (mm) za vrijeme bure od 12-18. 4. 1982 za odabrane stanice u Hrvatskoj

Station	Total precipitation amount (mm)	Station	Total precipitation amount (mm)
Zagreb	39.4	Pula-airport	19.2
Karlovac	63.4	Rijeka-airport	12.0
Ogulin	113.3	Senj	75.1
		Zadar-airport	16.8
Zavižan	102.6	Split	14.9

speed on Tito's Bridge of 44 m s^{-1} indicated earlier it must be emphasized that they were registered with a very sensitive anemograph (Vučetić, 1984). Straying from the Dinaric barrier toward the sea the bora wind speed decreased (Yoshino, 1976; Makjanić, 1970), and the observed maxima gusts were weaker at Pula-airport (23.2 m s^{-1}) and Mali Lošinj (13.0 m s^{-1}).

The temporal changes of surface meterological elements can be followed on diurnal courses for selected stations shown in Figs. 4-12. Although hourly precipitation amounts are not registered at Karlovac, Pula-airport and Zadar-airport, and therefore not indicated on daily courses some rainfall was measured during the period of 24 hours. The existence of mesocyclone on the middle Adriatic on 14 April could also be noticed from the daily course of pressure in Zadar and Split (Figs. 11-12). The next day the anticyclone over western Europe intensified and air pressure increased over the upstream and downstream bora region.

The bora case on 15 April was classified as the "anticyclonic" type (Smith, 1984; Hoinka 1985) following the previous day bora associated with the mesocyclone in the middle Adriatic and this defined as the "cyclonic" type.

During the bora wind the relative humidity was high (about 100 %) in the continental part and the temperature was near 0° C. The coastal area was characterized by higher temperature (4°-8° C). All stations marked the absence of normal diurnal temperature variation. The bora onset at all considered stations was accompanied by a sudden drop of relative humidity, decrease in temperature and increase of pressure and wind speed (in Senj 10 m s^{-1} during 4 hours). It should be noticed that the bora on different locations appeared from various directions between 0 and 90 degrees, as a consequence of specific local topography. The well known characteristic direction for the bora at Senj is ENE, where a strong bora usually has the longest duration. In the considered case study 12 - 18 April bora persisted 115 hrs with mean hourly speed greater than 10 m s^{-1} (Fig. 8). In the other places a strong bora (mean hourly speed > 10.0 m s^{-1}) lasted only a day or less. The surface characteristics of this bora

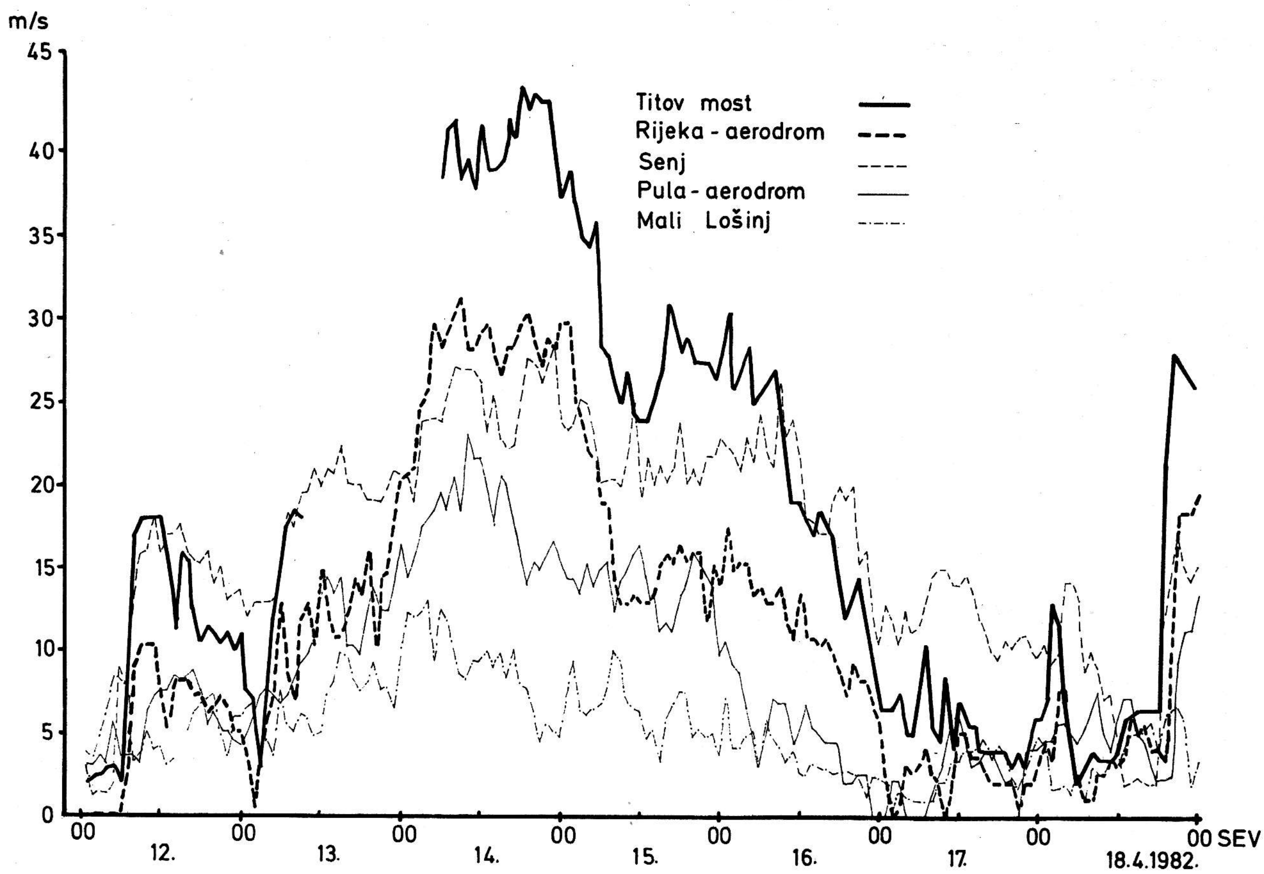


Fig. 3. Hourly values of maxima gusts for selected stations on the northern Adriatic for period 12 - 18 April 1982

Sl. 3. Satne vrijednosti maksimalnih udara za odabrane stanice na sjevernom Jadranu za period 12-18. 4. 1982.

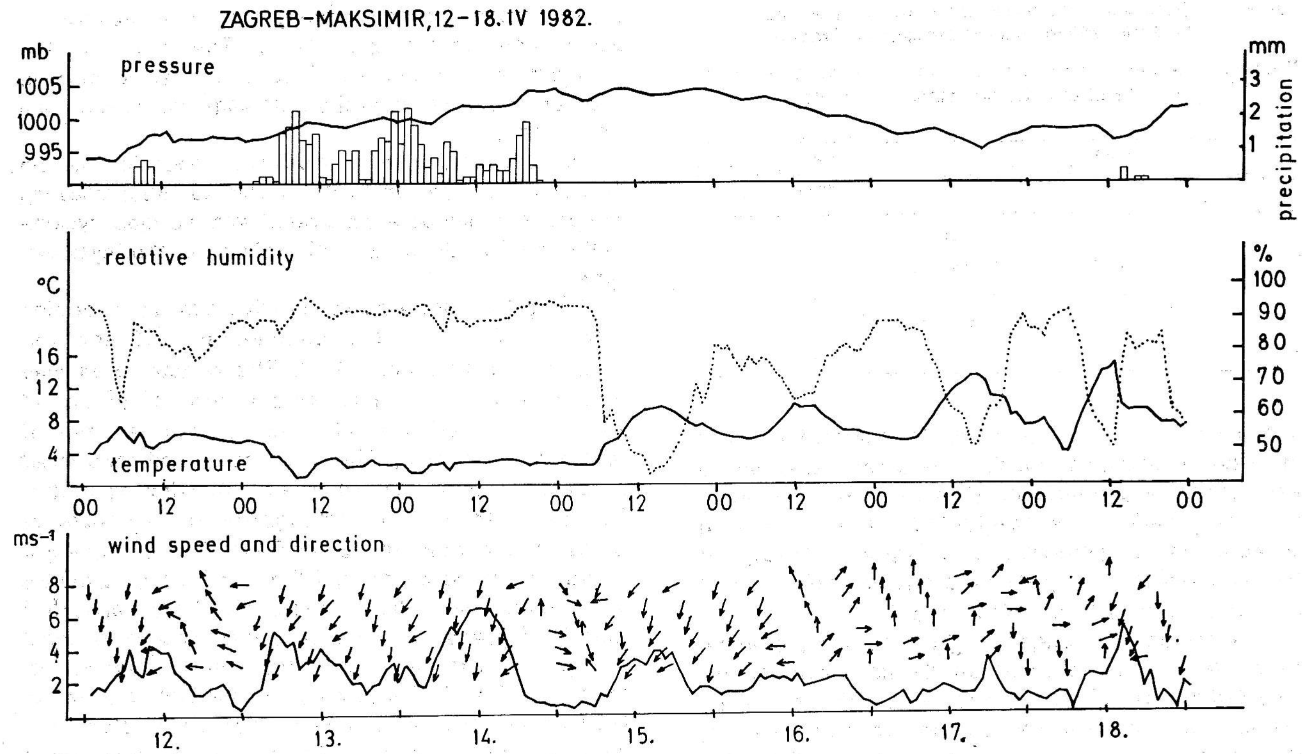


Fig. 4. Daily course of hourly values of air pressure, precipitation, temperature, relative humidity and mean of hourly values wind speed and direction on 12 -18 April 1982 for Zagreb-Maksimir

Sl. 4. Dnevni hodovi staničnog tlaka zraka, oborine, temperature, relativne vlage i srednje satne vrijednosti brzine i smjera vjetra od 12-18. 4. 1982 za Zagreb-Maksimir

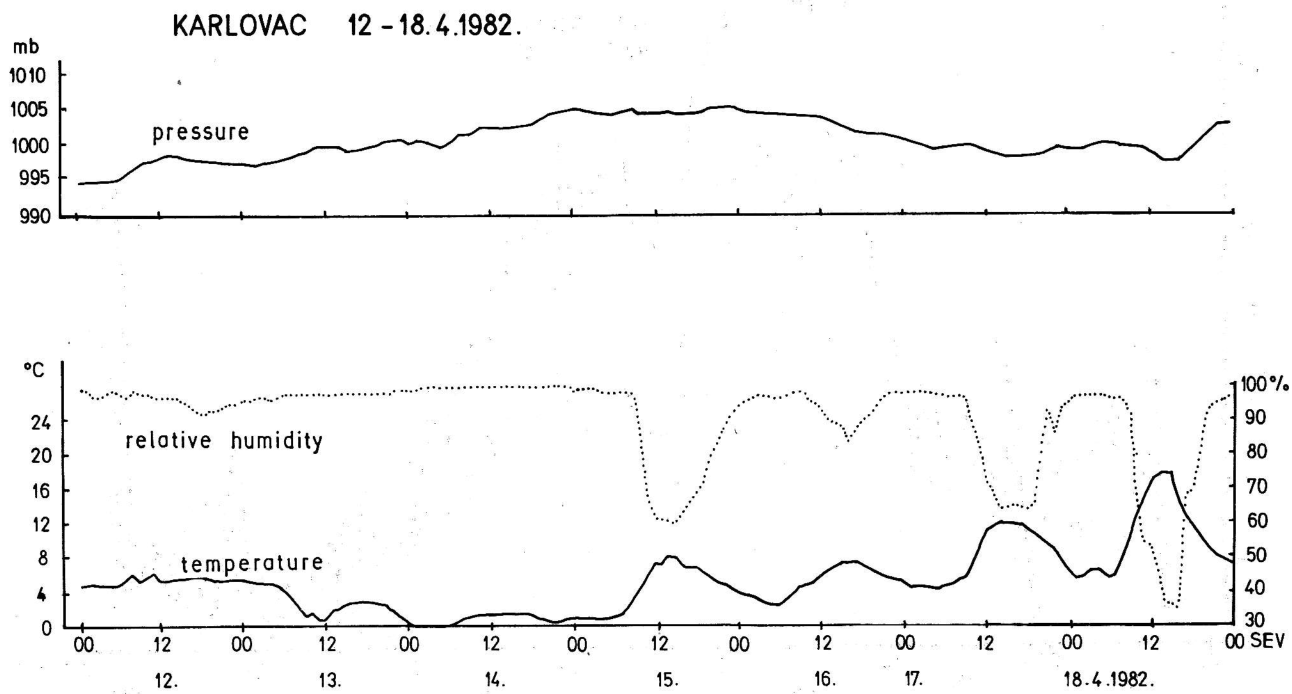


Fig. 5. Same as Fig. 4 except for Karlovac and without precipitation and wind daily course.

Sl. 5. Isto kao na slici 4. (samo bez oborine i vjetra) za Karlovac

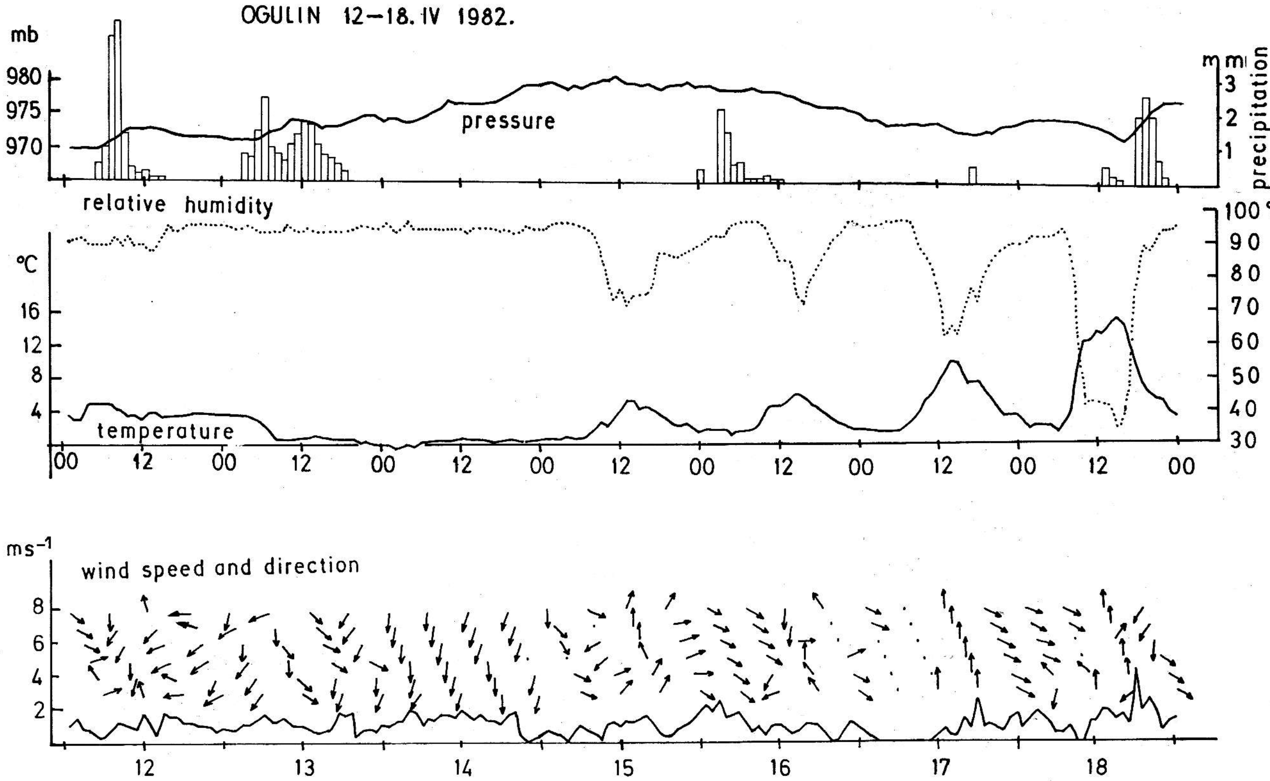


Fig. 6. Same as Fig. 4 except for Ogulin

Sl. 6. Isto kao na slici 4. samo za Ogulin

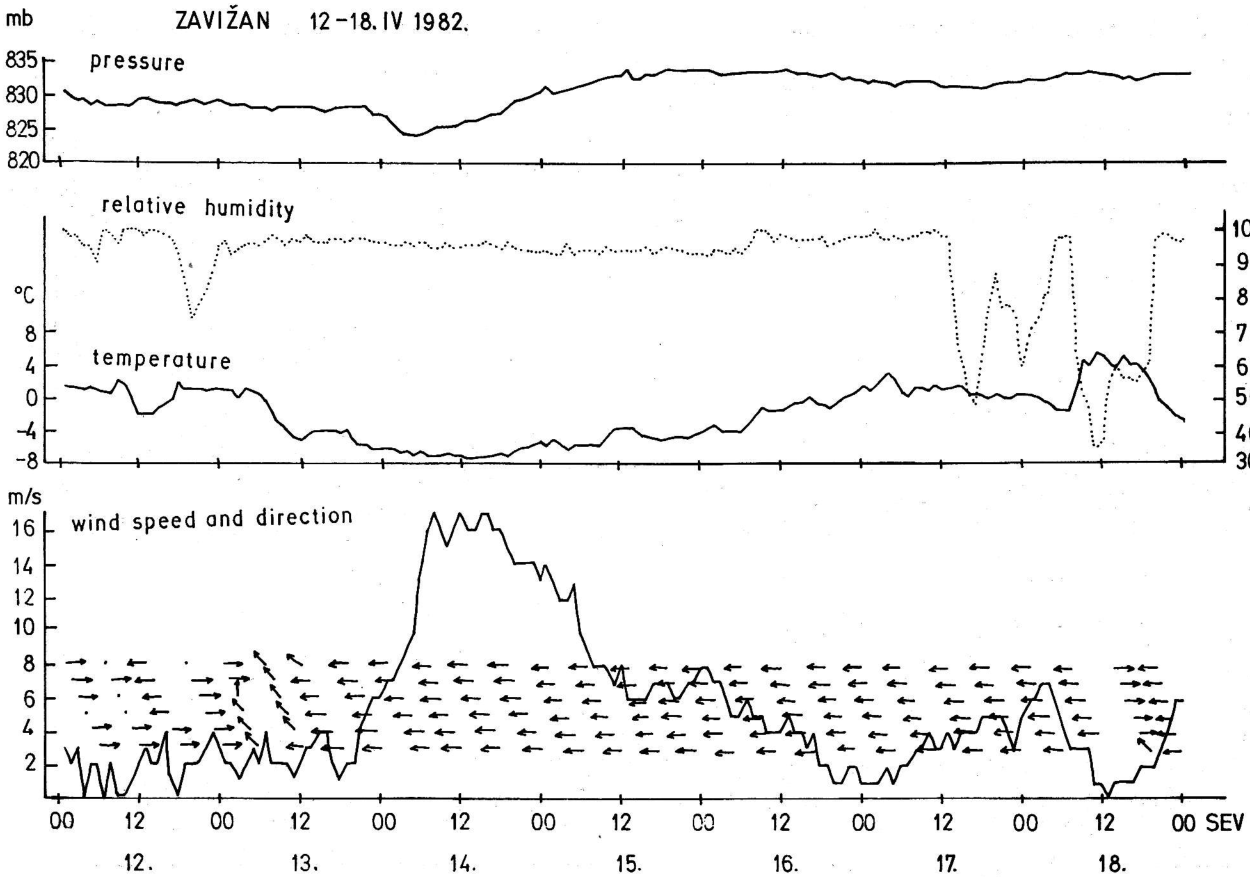


Fig. 7. Same as Fig. 4 except for Zavižan and without precipitation daily course.

Sl. 7. Isto kao na slici 4. (samo bez oborine) za Zavižan

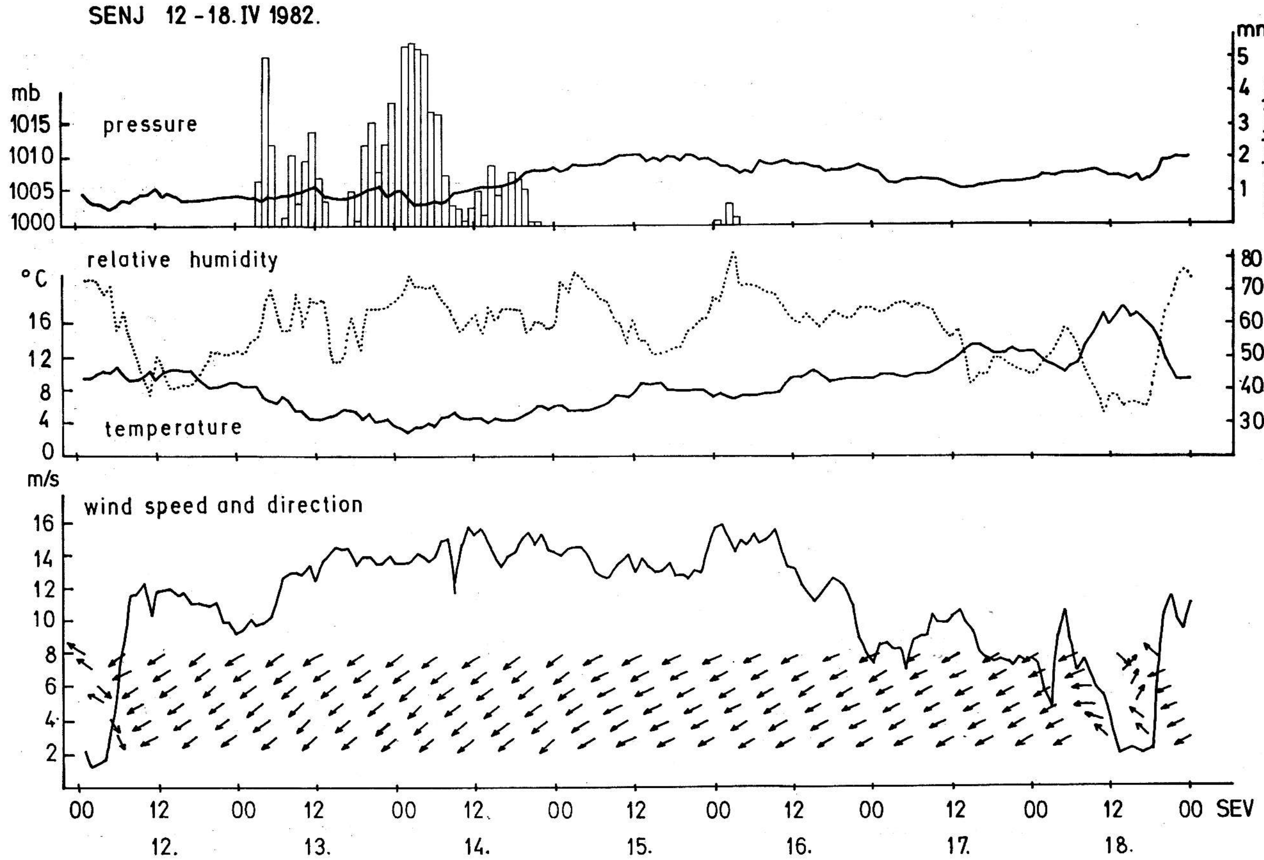


Fig. 8. Same as Fig. 4 exept for Senj

Sl. 8. Isto kao na slici 4. samo za Senj

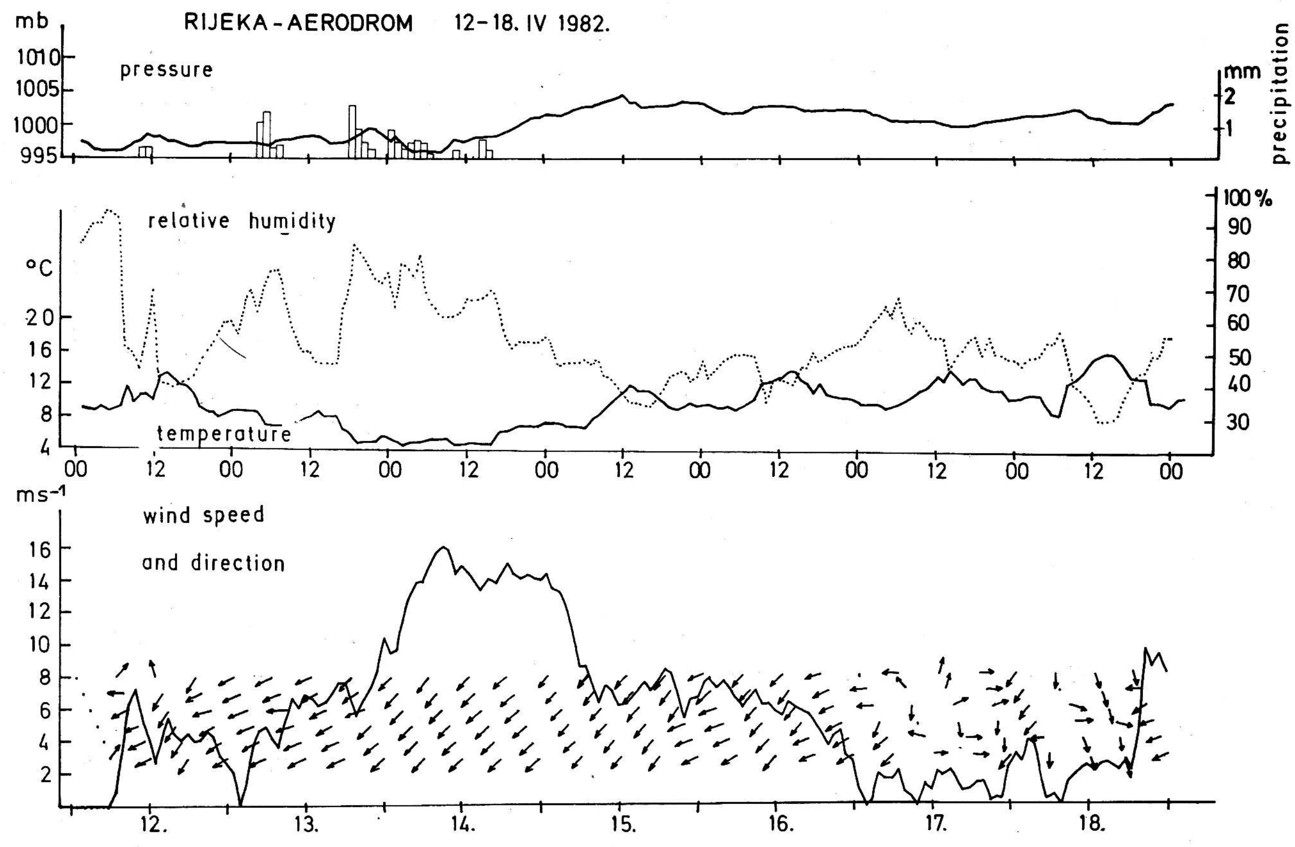


Fig. 9. Same as Fig. 4 exept for Rijeka-airport

Sl. 9. Isto kao na slici 4. samo za Rijeku-aerodrom

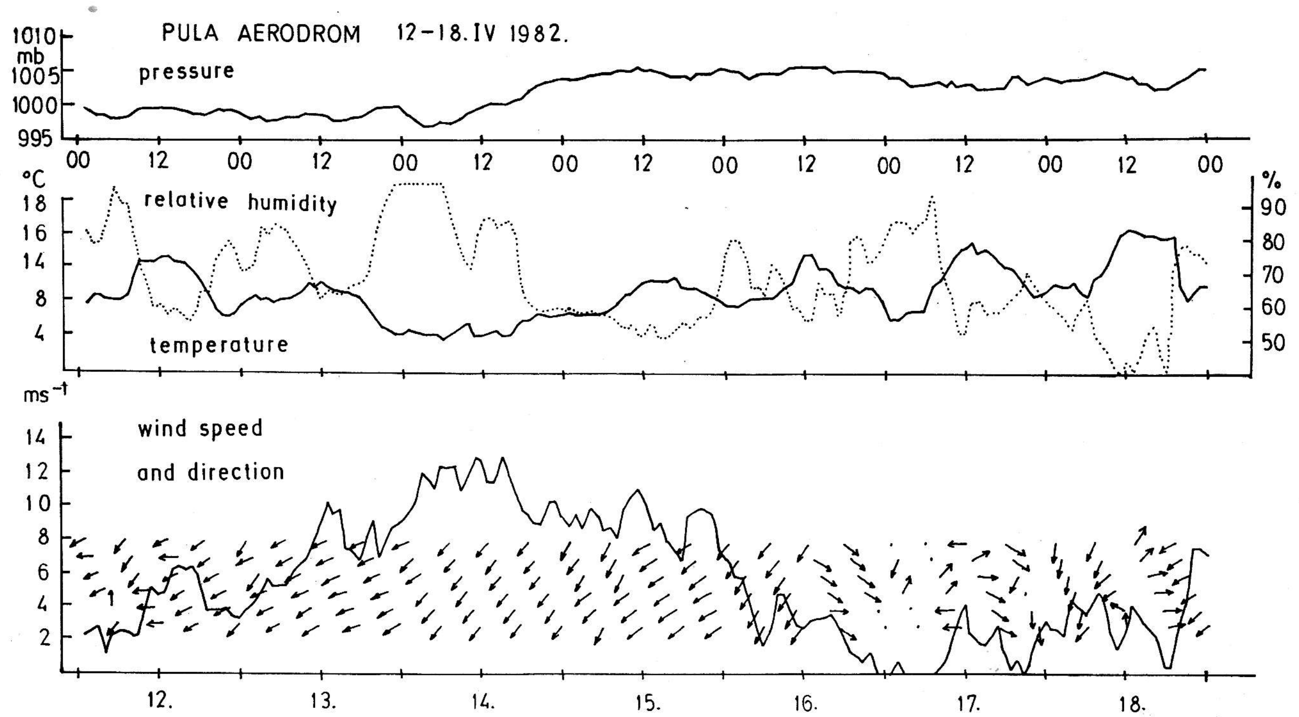


Fig. 10. Same as Fig. 4 except for Pula-airport and without preciptation daily course

Sl. 10. Isto kao na slici 4. (samo bez oborine) za Pulu-aerodrom

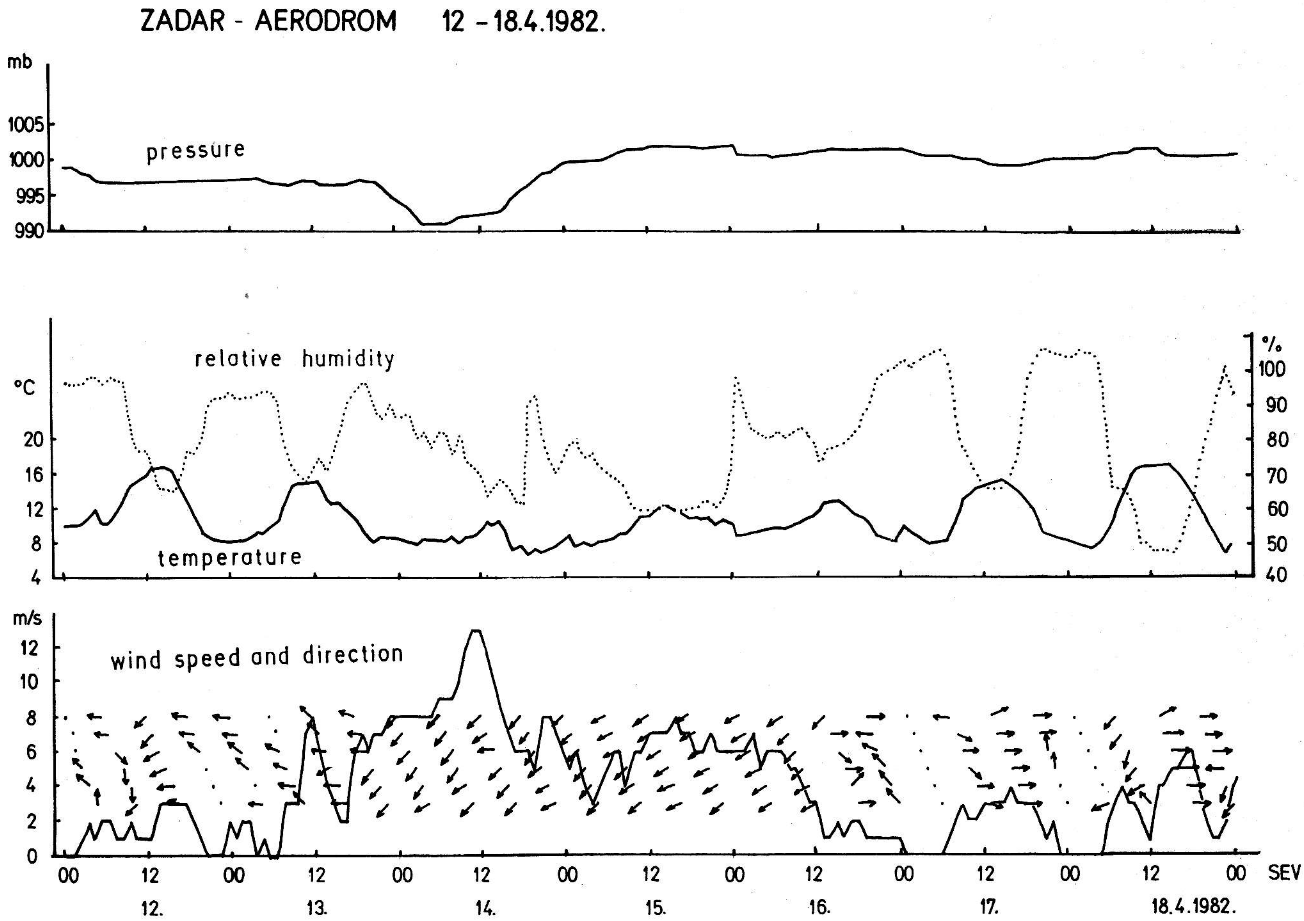


Fig. 11. Same as Fig. 4 except for Zadar-airport and without precipitation daily course.

Sl. 11. Isto kao na slici 4. (samo bez oborine) za Zadar-aerodrom

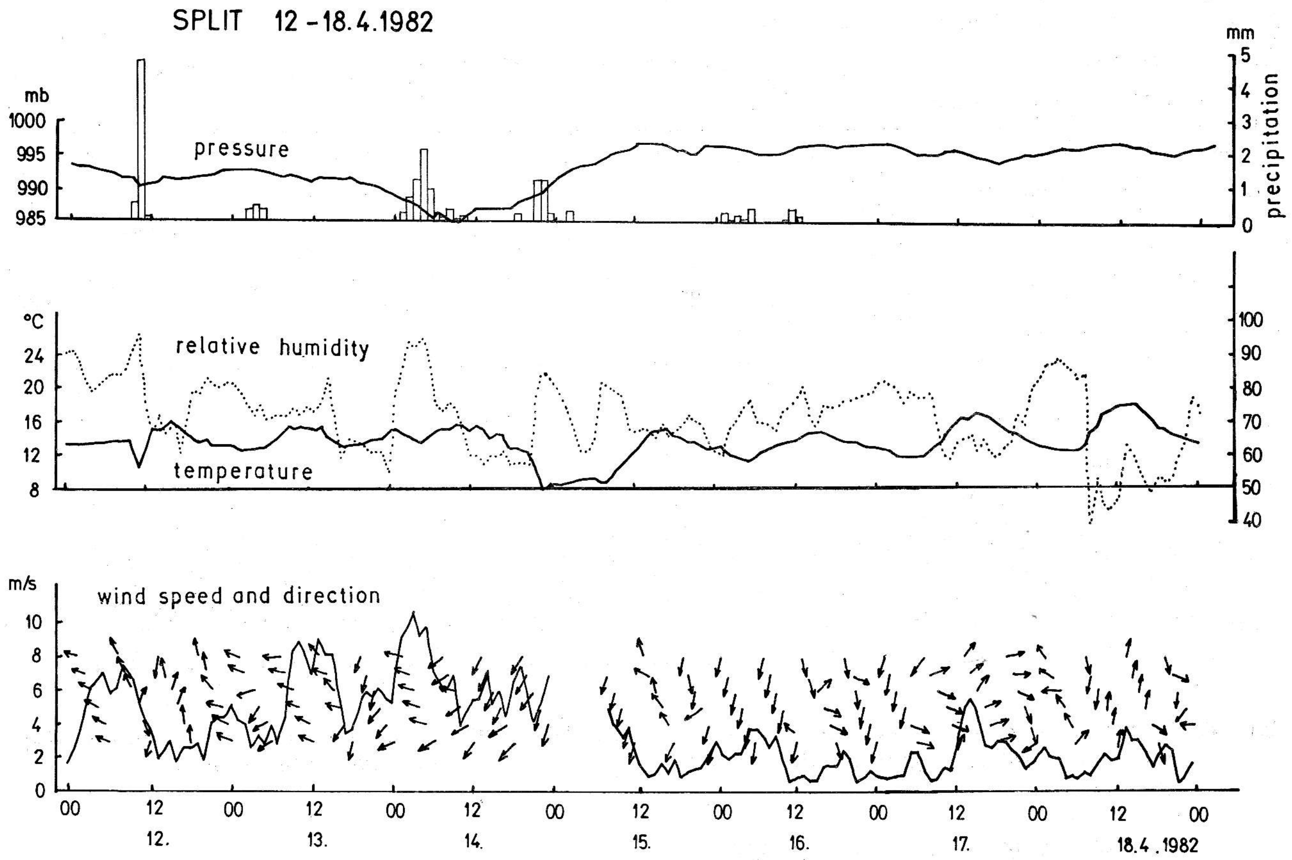


Fig. 12. Same as Fig. 4 exept for Split

Sl. 12. Isto kao na slici 4. samo za Split

case were accompanied by a specific vertical structure of atmosphere.

3. THE VERTICAL WIND STRUCTURE

Many authors have investigated the vertical structure of bora wind for this case (Smith 1982, 1984, 1987; Hoinka, 1985; Pettre, 1984; Klemp and Durran, 1987), but have mostly analysed bora areal observations on 15 April when the bora was weaker and the low tropospheric structure different in respect to stronger bora events on 14 April 1982. Smith shows that the bora display strong similarities to hydraulic flows which become supercritical over the crest of the mountain, accelerate down the lee slope and then dissipate their energy within a hydraulic jump.

3.1 Bora Layer

Unique definition of the bora layer does not exist. The bora layer is defined by the wind direction from 0°-90° (Yoshino, 1976). Smith (1987) defines it by a level at which the wind direction turns to 60° ± 45°. We also take into consideration the level where NE "bora component" (u_B = 45° ± 90°) is vanishing.

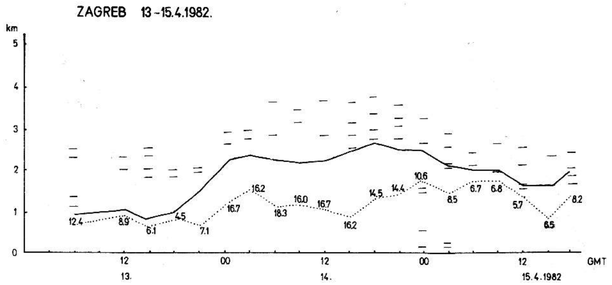
The existing analysis of low tropospheric velocity field in the upstream bora region for the considered situation shows a prevailing NE wind at the first 2-2.5 km altitudes. On the lee side (Pula) the bora layer was somewhat lower (1.5-2 km) and the wind there had a more pronounced easterly component. The maximum wind speed inside layer was measured on 14 April at 06 GMT on the upstream bora region (Zagreb 18.3 m s^{-1} at 1165 m altitude) and three hours later on the lee side (Pula 20.9 m s^{-1} at 618 m, Zadar 20.1 m s^{-1} at 684 m altitude), shown in Figs. 13 and 14. Appearance of the maximum wind velocity at Karlovac could not be exactly determined since the radiosounding measurements were available on 14 April only at 12 GMT and afterwards with the maximum wind speed of 18.6 m s^{-1} at 18 GMT.

The top of the bora layer on the windward side was approximately the same as the base of the first inversion layer (Fig. 13). It is essential that in this case the top of the bora air coincides with the height of the maximum NE wind speed at the bora onset and ending.

3.2. Stability and Wind Shear

The results of laboratory experiments and theory given by Smith (1986) indicate that due to wind turning through the strongly stratified layer only about half of the inversion layer descends. This is also noticed in Pula (Figs. 15 and 17). The double inversion appeared on 14/15 April at 0.5 - 0.7. km and 2 - 2.5 km altitudes. This agrees with the descending lower part of the inversion toward the sea observed during the flight on 15 April (Smith, 1987).

The low tropospheric structure above Zadar pointed out the differences in the structure in respect to other stations. In Zadar the bora onset was in the night hours on 13 April (Fig. 11) where the bora layer was thinner in



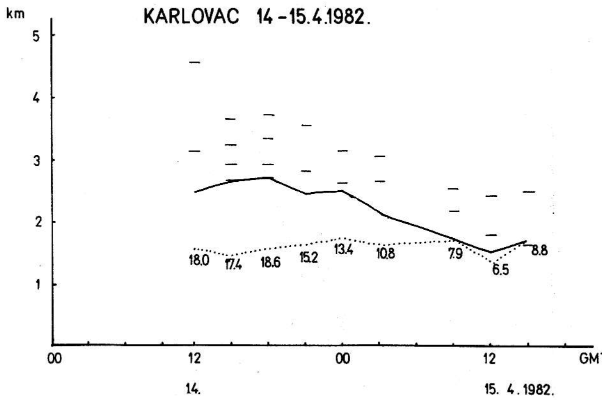
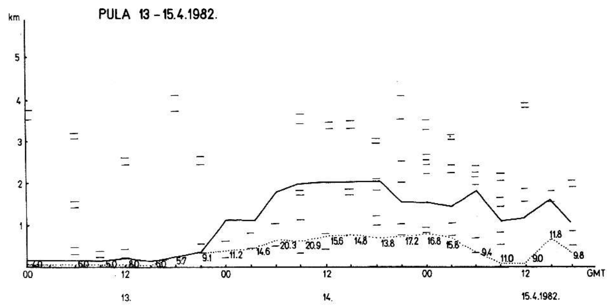


Fig. 13. The maximum thickness of the bora layer (-) the maximum wind speed inside the bora layer (...) and the inversion layers (=) on 13 - 15 April 1982 for Zagreb and Karlovac on 14-15 April 1982

Sl. 13. Maksimalna debljina sloja bure (---), maksimalna brzina vjetra unutar sloja bure (...) i slojevi inverzije (=) od 13-15. 4. 1982 za Zagreb i Karlovac od 14-15. 4. 1982.



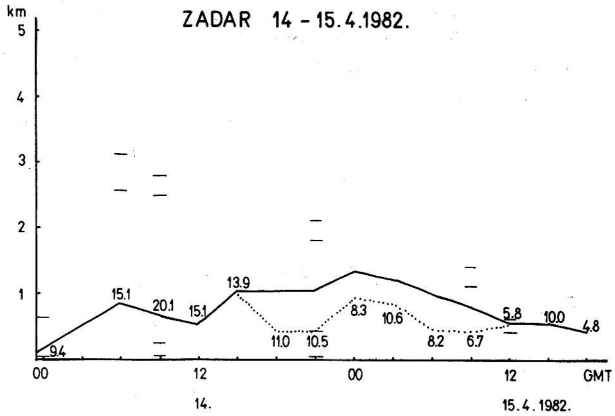


Fig. 14. Same as Fig. 13 except for Pula and Zadar

Sl. 14. Isto kao na slici 13. samo za Pulu i Zadar

The vertical distribution of moisture in the upstream and downstream region (Fig. 18) illustrates the large value of mixing ratio inside the bora layer decreasing gradually in height during the strongest bora. The next day when the bora was weakening the aircraft observed the moisture maximum in the southerly flow. Since the stability of moist atmosphere changes significantly in respect to the dry air, the moist processes should be taken into account in the bora structure.

The vertical wind structure in the upstream bora region and Pula (Figs. 20-22) shows that the wind direction turned abruptly from the NE to the SW through the stable layer. In Zadar where the inversion was not pronunced the wind direction changed gradually in height (Fig. 23). Thus the inversion was not continuously present during the bora period.

The aircraft did not fly inside the upstream bora air therefore the upstream acceleration was not observed directly. In the downstream the strongest turbulence was located at the lowest flight level (at 880 m) near Senj.

4. APPLICATION OF HYDRAULIC THEORY

Smith and Sun (1987) formulated a generalized hydraulic model for severe downslope wind presentation. The model is based on the idea of decoupling of the low-level accelerated flow from the undisturbed flow aloft. Several special cases were considered.

1. The stability profile consists of two layers: a neutral lower layer and a stable upper layer.
2. When the lower neutral layer becomes thin, the problem reduces to the continuos stratification system (Smith, 1985).
3. If the stable layer is thin in comparison with the total depth the problem reduces to the shallow water system (Long, 1954). The hydraulic theory was applied to five ALPEX bora cases using available aircraft measurements. The results indicate a considerable agreement.

The same comparison of upstream conditions with the prediction of hydraulic theory is done here on 13, 14 and 15 April at 12 GMT. As indicated in section 3.1 the bora layer H_o is defined as the layer with the wind direction between 15^o - 105^o (Smith, 1987). In our situation the so defined layer coincides with the layer in which the bora component ($45^o \pm 90^o$) was positive, und $u_B = 0$ is indentical with H_o in Smith (Figs. 24 and 25). In the same way H_o is defined in another bora case presented by Jurčec in this Volume.

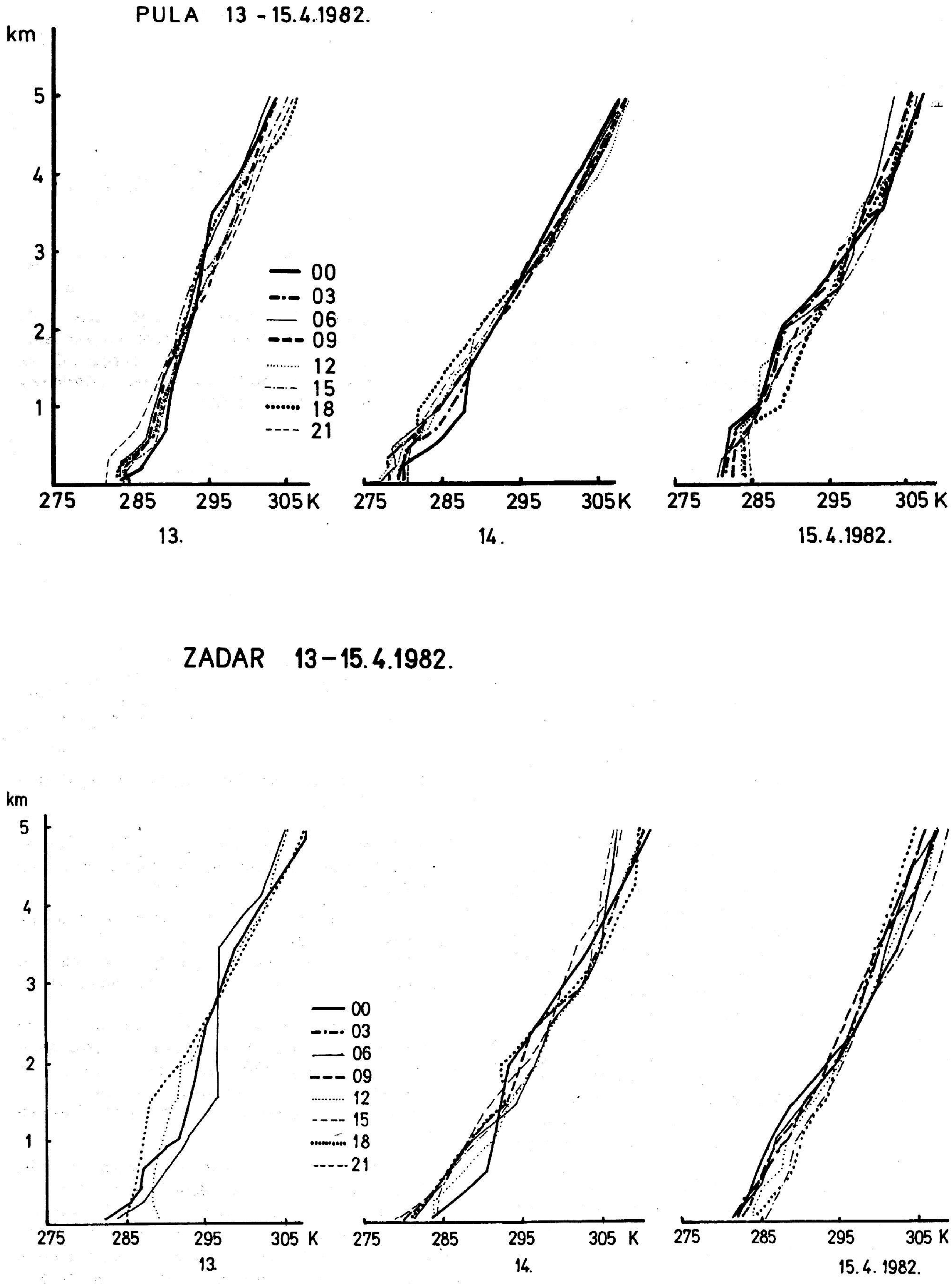


Fig. 15. The vertical profiles of potential temperature on 13 - 15 April for Pula and Zadar

Sl. 15. Vertikalni profil potencijalne temperature od 13-15. 4. 1982. za Pulu i Zadar

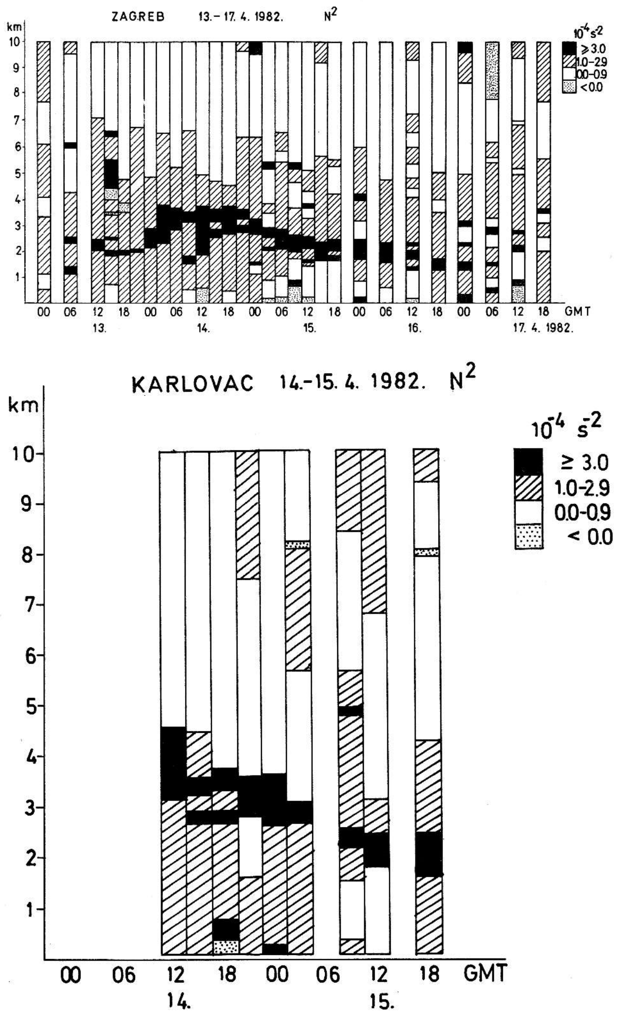


Fig. 16. Time-height cross section of stability N^2 (10^{-4} s^{-2}) over Zagreb for period 13 - 17 April 1982 and Karlovac for period 14-15 April 1982.

Sl. 16. Vremenski vertikalni presjek stabilnosti N^2 (10^{-14} s^{-2}) nad Zagrebom za 13-17. 4. 1982 i Karlovac za 14-15. 4. 1982.

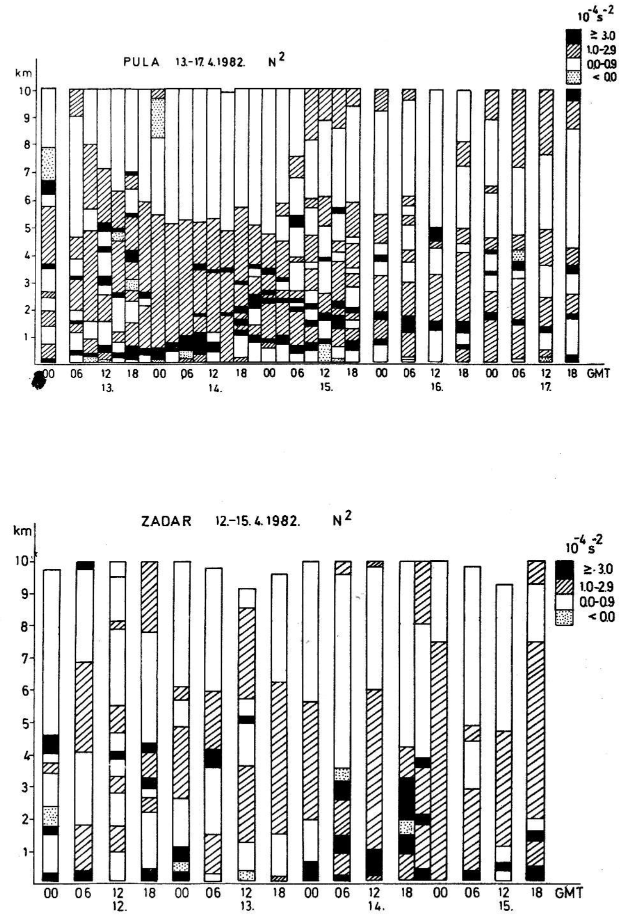


Fig. 17. Same as Fig. 16 except for Pula and Zadar.

Sl. 17. Isto kao na slici 16. samo za Pulu i Zadar

The analysis of the bora upstream stability profile (Figs. 16 and 26) shown as the Brunt-Väisälä frequency, indicates mainly two layers with an approximately lower neutral layer $N_1 \approx O$ and an upper layer of constant stability N_2 on 14 and 15 April. The observed and calculated hydraulic parameters are given in Tables 3 and 4 according to radiosounding data of Zagreb and Karlovac.

A prediction for the height δ_p of the split streamline δc and the theoretical mountain height h_p associated with the observed d are obtained graphically from Smith and Sun (1987, Fig. 2). The mountain height is 800 m as in Smith's paper. The values of d and d_p are similar, comparison with the same layer at the other stations (Fig. 14). The inversion layer above Zadar occured only in a short period, mainly as surface inversion or above the bora layer (Figs. 14 and 15; Table 2). But bora wind was there weaker than on the northern Adriatic.

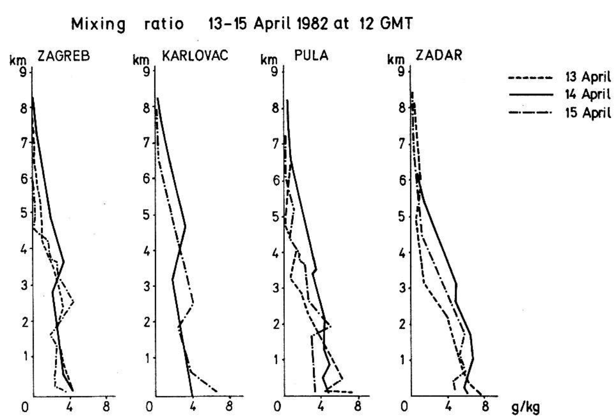


Fig. 18. Vertical profiles of mixing ratio for Zagreb, Karlovac, Pula and Zadar on 13-15 April 1982 at 12 GMT

Sl. 18. Vertikalni profil omjera miješanja za Zagreb, Karlovac, Pulu i Zadar od 13-15. 4. 1982 u 12 GMT

Table 2. The stability N^2 (10^{-4} s^{-2}), for inversion layers in Zagreb, Karlovac, Pula and Zadar on 13 - 15 April 1982. * indicates lack of data

Tabela 2. Stabilnost N^2 (10^{-4} s^{-2}) slojeva inverzije u Zagrebu, Karlovcu, Puli i Zadru za 13-15. 4. 1982. * nema podataka

	ZAGREB		KARLOVAC		PULA		ZADAR	
DAY	LAYER	N^2	LAYER	N^2	LAYER	N^2	LAYER	N^2
13. April 1982.								
00GMT					43-196	5.15	376-1140	0.51
					3518-3674	2.45		
06GMT	1142-1380	1.73			345-498	4.12	84-302	5.56
	2321-2532	2.79			1474-1585	3.56		
					3096-3201	3.91		
09GMT					265-404	3.74		
12GMT	2025-2424	1.11						
15GMT	1854-2062	2.80			257-459	2.86		
	2465-2539	11.65			2471-2620	3.91		
18GMT					3734-4143	1.07		
21GMT	1987-2087	7.18			368-575	1.84		
					2439-2637	2.46		
14. April 1982.								
00GMT	2646-2919	1.18			214-612	1.31	84-692	1.40
03GMT	2794-2959	5.18			474-810	1.66		
06GMT	2855-3652	0.21			504-1047	0.80	2621-3192	0.67
09GMT	3154-3480	2.77			371-1174	0.45	84-294	7.43
					1766-1860	7.27	2534-285	1.90
					3462-3673	1.82		
12GMT	2875-3697	0.59	3144-4579	0.27	475-805	1.66		
					3356-3467	5.30		
15GMT	2534-2824	3.70	2697-2935	2.44	1782-1876	7.64		
	3159-3640	1.08	3261-3590	2.19	3361-3502	3.61		
18GMT	2704-2977	2.12	2711-2939	3.37	1070-1253	2.90		
	3436-3762	1.23	3359-3754	2.40	1879-2126	2.11		
					2926-3027	5.17		
21GMT	2750-3036	2.38	2829-3593	0.97	788-1069	1.26	84-472	3.66
	3264-3583	1.84			2054-2562	0.94	1849-2168	1.94
					3524-3633	7.11		
15. April 1982.								
00GMT	128-520	0.42	2659-3198	1.19	801-953	4.03		
	1484-1578	5.11			2232-2436	2.43		
	2676-3244	1.02			2543-2697	2.80		
					3293-3505	2.33		
03GMT	128-204	1.41	2691-3089	2.04	761-1050	1.44		
	2041-2141	6.53			2252-2410	4.84		
	2563-2889	2.61			3030-3161	5.56		
06GMT	2105-2811	0.77			403-688	1.92		
					1925-2107	3.97		
					2252-2399	4.46		
09GMT	1986-2614	0.99	2209-2584	2.20	513-812	3.69	1135-1417	2.48
					1419-1633	2.52		
					2056-2205	6.48		
12GMT	1551-1646	9.59	1823-2482	0.86	1612-1868	2.10	438-656	4.36
	2124-2561	1.64			3808-3901	13.16		
15GMT	1648-2357	0.17			1521-1802	1.32		
18GMT	1668-1832	3.07	1654-2510	0.55	538-878	1.13		
	2028-2428	1.80			1905-2088	2.60		

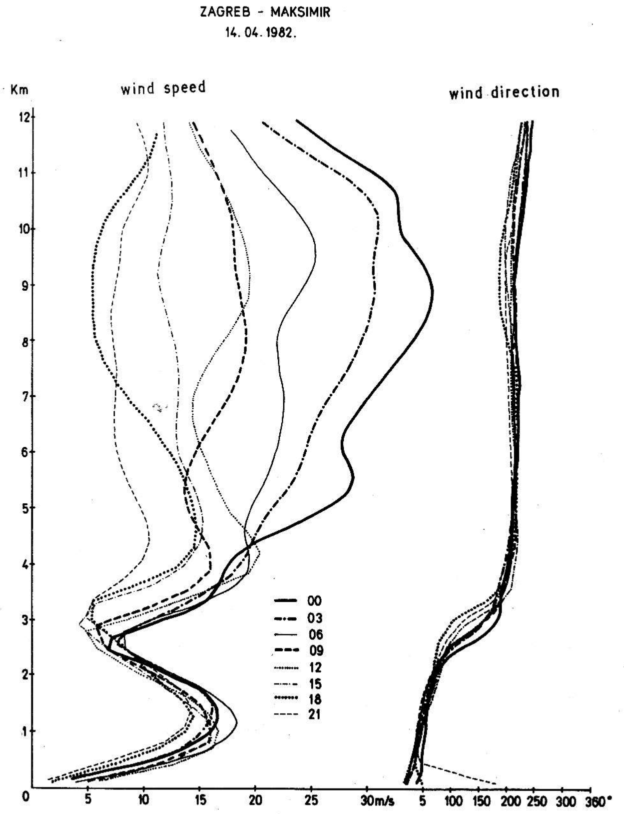


Fig. 19. Vertical profiles of wind speed (left) and wind direction (right) on 14 April 1982 for Zagreb
Sl. 19. Vertikalni profil brzine vjetra (lijevo) i smjera vjetra (desno) za 14. 4. 1982. za Zagreb

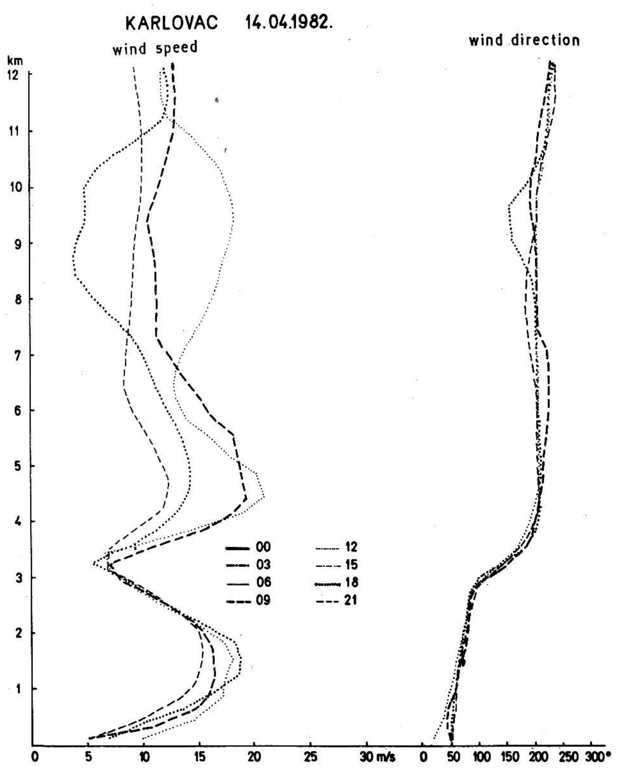


Fig. 20. Same as Fig. 19 except for Karlovac
Sl. 20. Isto kao na slici 19. samo za Karlovac

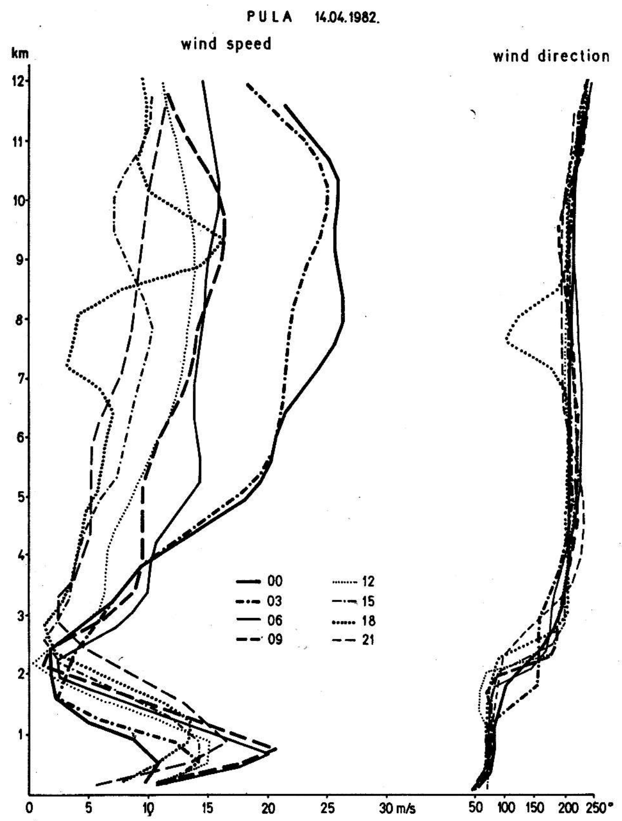


Fig. 21. Same as Fig. 19 except for Pula
Sl. 21. Isto kao na slici 19. samo za Pulu

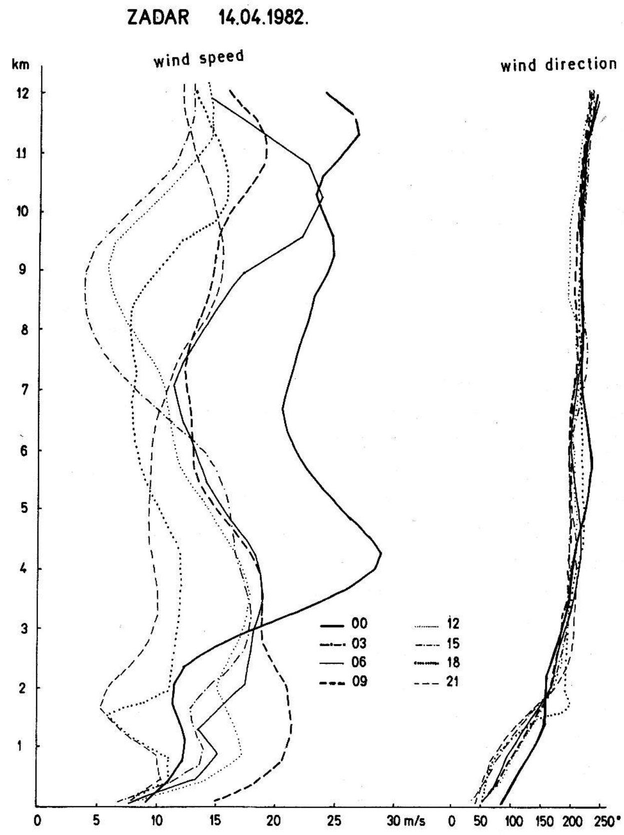


Fig. 22. Same as Fig. 19 except for Zadar
Sl. 22. Isto kao na slici 19. samo za Zadar

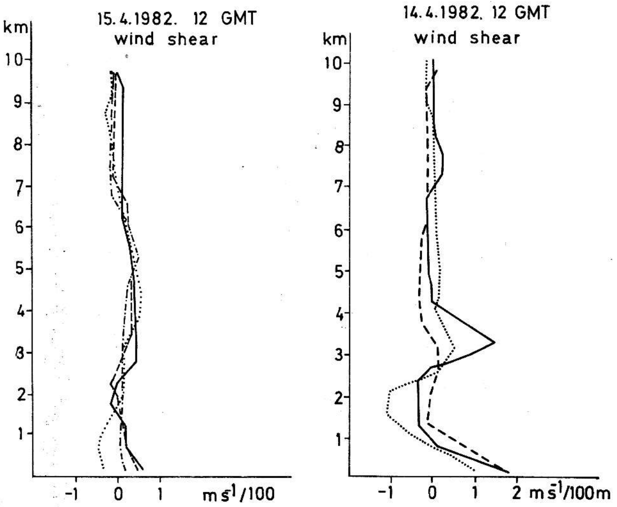


Fig. 23. The vertical profiles of wind shear for Zagreb, Karlovac, Pula and Zadar

Sl. 23. Vertikalni profili smicanja vjetra za Zagreb, Karlovac, Pulu i Zadar

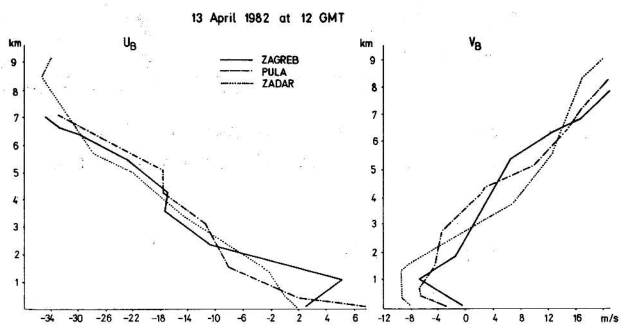


Fig. 24. Vertical profiles of u_B and v_B "bora component" on 13 April 1982 at 12 GMT

Sl. 24. Vertikalni profil u_B i v_B "komponente bure" za 13. 4. 1982

The square of Brunt-Väisällä frequency $N^2 = \frac{g}{\theta}\frac{\partial\theta}{\partial z}$ is proportional to static stability of the atmosphere. Therefore, vertical time cross-sections for N^2 at Zagreb, Karlovac, Pula and Zadar are shown (Figs. 16-17). On 14 April when the bora was strongest, the upstream stable layer (approximately $3.10^{-4}\ s^{-2} < N^2 < 8\ .\ 10^{-4}\ s^{-2}$) existed continuously about 2.8 - 3.7 km altitudes. While the bora was weakening (15 April) this layer descended at 2 - 2.6 km altitude. In Zadar the maxima value of N^2 was about $4.10^{-4}\ s^{-2}$ (Fig. 17 and Table 2).

indicating that the height of split streamline can be predicted. The comparison of hydraulic parameters on 15 April somewhat differ from the results of Smith and Sun (1987. Table 1) due to the smaller value of U.

On 13 April the low troposhere was continuously stratified (Fig. 24) and therefore we can follow Smith (1985, 1987) in the calculation of the height of the dividing streamline and Froude number $F_o = U/NH_o$ for continuous type. The theoretical value of the critical layer H_o^* for critical mountain height.

$h = h^*,\ \delta = \delta^*$ at $\partial h/\partial\delta = 0$

is obtained by

$$\hat{H}_o^* = \hat{h}^* - \hat{\delta}^* + \arccos\frac{\hat{h}^*}{\hat{\delta}^*}$$

$$\hat{\delta}^* = -\frac{1}{\sqrt{2}}\left[\hat{h}^{*2} + \hat{h}^*\left(\hat{h}^{*2} + 4\right)^{1/2}\right]^{1/2}$$

$$\hat{h}^* = l\,\hat{h}^* \qquad \hat{\delta}^* = l\,\hat{\delta}^* \qquad \left(l = \frac{N}{U}\right.$$

is the Scorer parameter)

Predicted H_o^* is higher for 2.5 km than the empirical H_o. This large difference was found for the first day at the bora onset. The agreement is better on 14 April with bora strengthening. We neglect the thin neutral layer of 500 m capped by the stable layer 2000 m (Fig. 25). N-profile approximates a continuously stratified atmosphere and analysis reduce to the Smith (1985) model (Table 3 and 4 for continuous type). The small theoretical and empirical Froude numbers are rather close and indicate the possibility of an hydraulic jump on the downstream bora region.

The next step in the application of theory is the prediction of the vertical profile lee wind, u (x_1, z) using

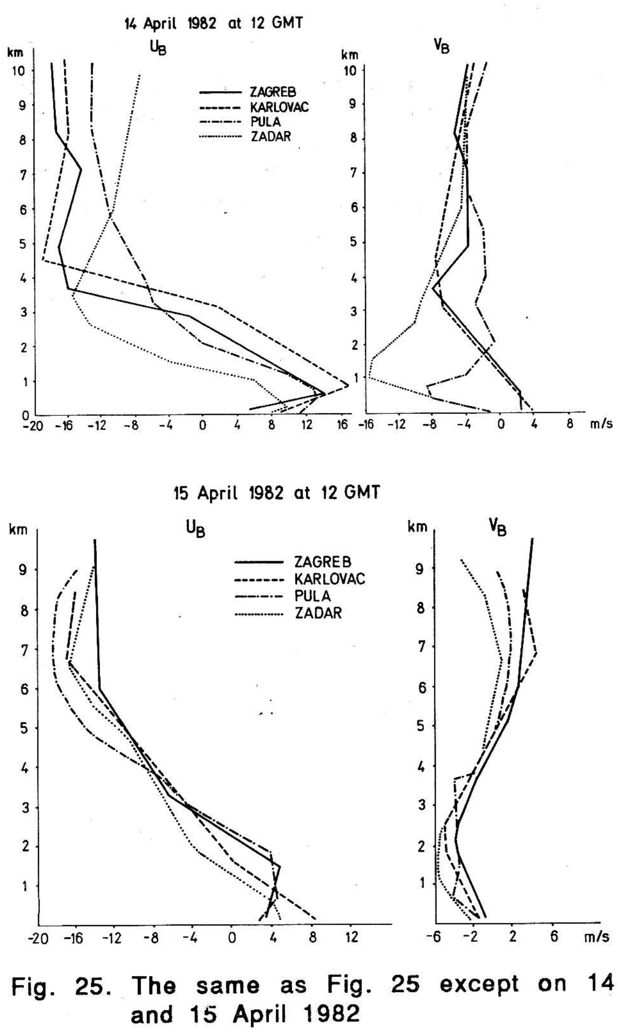


Fig. 25. The same as Fig. 25 except on 14 and 15 April 1982

Sl. 25. Isto kao na slici 25. samo za 14. i 15. 4. 1982

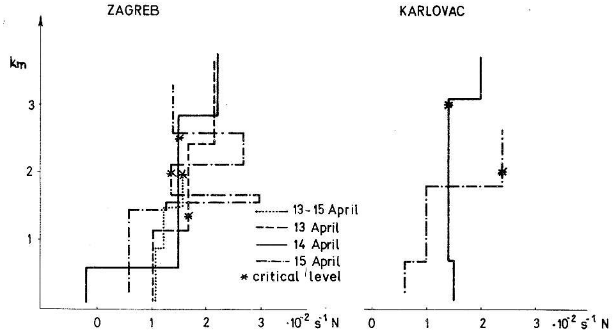


Fig. 26. Vertical profiles of the Brunt-Väisälä frequence over Zagreb and Karlovac for 13 - 15 April 1982.
Sl. 26. Vertikalni profili Brunt-Väisälä frekvencije nad Zagrebom i Karlovcem od 13-15. 4. 1982

δ_{c1} as a descending streamline in point x_1 (h=o) on the lee side. δ_{c1} is obtained graphically from Smith (1985, Fig. 2) for the "positive mountain", with the final terrain height being equal downstream and upstream.

Using Zagreb and Karlovac vertical wind and stability profiles the theoretical streamline δ_c descends about 1 km over the ridge crest and about 2.5 km on the lee side where h = o (Table 3 and 4). A prediction for the lee surface wind is about 50 m s^{-1} and it is relatively close to the observed maximum of 44 m s^{-1} on Tito's Bridge. The height of $H_1^* = H_o^* + \delta_u$ at which the lee wind speed is the same as upstream (u (x_1, z) = U) is 1300 m and 1600 m for using Zagreb and Karlovac respectively. The comparison of predicted value with the observed value according to sounding

Zagreb H_o = 2600 m H_o^* = 3900 m
Pula H_1 = 1500 m H_1^* = 1300 m

and the aircraft data on 15 April along sections Zagreb - Senj (Fig. 9b) and Zagreb - Krk (Fig. 10b in Smith 1987.) show some difference. This would mean that the hydraulic solutions overestimate the height of disturbed bora flow (H_o^* = 3900 m). The result is much better when all available vertical wind and stability profiles are averaged for the period of 13 April at 06 GMT - 15 April at 18 GMT, as seen in Table 3. According to Smith (1985) the transitional flow for the effective mountain height greater than 1 is not possible. If we specify h = 1.0, for considered bora conditions the predicted maximum height (h_p) of the mountain is 500 m. This result indicates the transient flow over lower passes and may explain the longest bora duration in Senj.

On the last day when the bora ceased on most northern Adriatic stations the lower neutral layer deepened. Since the upper stability layer N_2 was thin the problem reduces to a single layered type, for which the critical mountain height for transition flow is given by Long (1954) relation

$$\frac{h}{H_o} = 1 + \frac{1}{2} F_o^2 - \frac{2}{3} F_o^{2/3}$$

$$F_o = U\,[g' H_o]^{1/2} \qquad g' = N^2 d_2$$

For h = 800m similar hydraulic parameters as in Smith (1987) are obtained (Table 3).

Taking theoretical value H_o^* and H_o according to hydraulic theory it is possible to determine the pressure drag D on the mountain:

$$D = \frac{\sigma N^2}{6} (H_o^* - H_1^*)^3$$

with density ρ = 1 kg m^{-3}, N = 0.015 s^{-1}, $H_o^* - H_1^*$ =2600 m on 14 April 1982.

$$D = 659 \times 10^3 \text{ kg s}^{-2}$$

The mountain pressure drag is a measure of the strength of the transitional flow and in our conditions it is equivalent to Δp = 8.2 hPa for the 800 m high mountain. The pressure difference is very close to the observed value of 8.5 hPa across the mountain. This means that the theoretically obtained splitting of the stable layer could explain this drag, but it would be underestimated if $H_o - H_1 \approx 1$ km as it looks from the observations. These differences are probably a consequence of many factors affecting the large pressure gradient which were neglected in the hydraulic theory.

The present application of the internal hydraulic theory therefore seems suitable for the presented case of postfrontal bora except at the bora onset.

5. SUMMARY AND CONCLUSION

The presented analysis of the mesoscale bora characteristic and the vertical atmospheric structure in the upstream and downstream bora region on 12 - 18 April 1982 indicates a few common features for the majority of the northern Adriatic boras.

The strongest bora was observed on Krk Island and at Senj with the longest duration at Senj. The bora onset was associated by a decrease in temperature and relative humidity and an abrupt increase in wind speed. Unlike the situation with the strongest bora during ALPEX-SOP (see Bajić in this Volume) in the considered case the cyclonic activity in the Gulf Genova was not observed. A large pressure gradient between the continental area and the coast is a consequence of the cold air supply in the upstream region and the mesocyclone over the middle Adriatic.

The vertical atmospheric structure during the strongest bora was characterized by pronounced maximum wind speed in the bora layer (wind direction between 15° - 105°) and the SW wind aloft. The stability profiles indicate the strong stable on the top of the bora layer. However, the part of the upstream inversion layer decoupled and descended toward the Adriatic Sea. The stable layer prevented vertical propagation of wave energy which is the typical condition during the bora events.

The flight mission on 15 April was preformed when the bora was already in a decaying stage at most places. The results of the generalized hydraulic theory application using the aircraft data (Smith and Sun, 1987) support the idea that the steady state hydraulic equations can be used to predict the split streamline

Table 3. Hydraulic parameters for period 13 - 15 April 1982 according to sounding of Zagreb

Tabela 3. Hidraulički parametri za period 13-15. 4. 1982 prema radiosondažnim podacima Zagreba

TWO - LAYER MODEL

DATE	h [m]	$\hat{h}$	N_{21} [s^{-1}]	U [m/s]	l [$10^{-3}m^{-1}$]	Θ_{crit} [K]	H_a [m]	d [m]	$r=\frac{d}{H_a}$	d_p [m]	h_p [m]
14 April	800	0.95	0.015	12.6	1.19	289	600	2020	3.37	3200*	300*
15 April	800	2.92	0.019	5.2	3.65	282	1460	540	0.37	930	680

* not in allowed region - chose boundary point

CONTINUOUS STRATIFICATION

DATE	h [m]	$\hat{h}$	N [s^{-1}]	U [m/s]	l [$10^{-3}m^{-1}$]	Θ_{crit} [K]	H_o [m]	F_o	H_o* [m]	F_o*	δ_c [m]	δ_{cl} [m]	u [m/s]	H_1* [m]
13 April	800	0.92	0.012	10.4	1.15	282	1500	0.55	4000	0.22	-1050	-2500	40.6	1400
14 April	800	0.95	0.013	12.6	1.19	289	2600	0.32	3900	0.22	-1050	-2600	51.7	1300
13-15 April	500	1.00	0.013	6.6	1.97	285	2000	0.25	2400	0.21	-900	-1600	27.6	800

SINGLE LAYER

DATE	h [m]	$\hat{h}$	N_2 [s^{-1}]	U [m/s]	l [$10^{-3}m^{-1}$]	Θ_{crit} [K]	H_o [m]	F_o	$\frac{h}{H_o}$ [m]	H_o*	F_o*	$(\frac{h}{H_o})$*
15 April	800	2.91	0.019	5.2	3.65	282	2000	0.26	**0.4**	1900	0.28	0.42

Table 4. Hydraulic parameters for period 14 - 15 April 1982 according to sounding of Karlovac

Tabela 4. Hidraulički parametri za period 14-15. 4. 1982 prema radiosondažnim podacima Karlovca

TWO - LAYER MODEL

DATE	h [m]	$\hat{h}$	N_2 [s^{-1}]	U [m/s]	l [$10^{-3}m^{-1}$]	Θ_{crit} [K]	H_a [m]	d [m]	$r=\frac{d}{H_a}$	d_p [m]	h_p [m]
15 April	800	3.20	0.024	6.0	6.0	287	1800	200	0.11	490**	1090**

** small r - use $H_{eff} = H_a + \gamma \cdot d$ $\gamma = 0.5 \pm 0.05$

$$\frac{h}{H_{eff}} = 1 + \frac{1}{2} F_o^{2} - \frac{3}{2} F_o^{2/3} \qquad F_o^{2} = \frac{U^2}{N_2^2 \, d \, H_{eff}}$$

CONTINUOUS STRATIFICATION

DATE	h [m]	$\hat{h}$	N [s^{-1}]	U [m/s]	l [$10^{-3}m^{-1}$]	Θ_{crit} [K]	H_o [m]	F_o	H_o* [m]	F_o*	δ_c [m]	δ_{cl} [m]	u [m/s]	H_1* [m]
14 April	800	0.80	0.015	15.0	1.0	292	3000	0.33	4300	0.23	-1100	-2700	55.5	1600

SINGLE LAYER

DATE	h [m]	$\hat{h}$	N_2 [s^{-1}]	U [m/s]	l [$10^{-3}m^{-1}$]	Θ_{crit} [K]	H_o [m]	F_o	$\frac{h}{H_o}$	H_o* [m]	F_o*	$(\frac{h}{H_o})$*
15 April	800	3.20	0.024	6.0	4.0	287	2000	0.40	0.40	3000	0.28	0.27

altitude. The same could be concluded from the results of the theory application during the different bora stages. The best agreeement between empirical and predicted hydraulic parameters was obtained for the mean atmosphere assuming the steady state during the entire bora period.

The main reason for differences between observed and predicted hydraulic parameters is the existence of pronounced wind shear and a large moisture amount in the upstream bora layer which may largey influence the stability profile.

Acknowledgement

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KRATAK SADRŽAJ

Proučavan je slučaj jake bure (12-18. 4. 1982) za vrijeme ALPEX-SOP koja je bila povezana sa prodorom hladnog zraka na Jadranu. Pojačani prizemni gradijenti tlaka opaženi su između nagomilanog hladnog zraka u navjetrini i mezociklone fomirane na srednjem Jadranu. Jaka bura zahvatila je samo područje sjevernog Jadrana, dok je na srednjem prevladavalo jugo. Maksimalne brzine vjetra zabilježene su 14. 4. na području otoka Krka (maksimalni udar vjetra od 44 m s^{-1} na Titovom mostu). Kao i u svim situacijama bure, početak je bio povezan sa padom temperature i relativne vlage te naglim povećanjem brzine vjetra (u Senju 10 m s^{-1} tokom 4 sata). Zbog specifičnog položaja Senja u podnožju Vratnika najdulje trajanje bure (138 sati) u ovoj situaciji zabilježeno je na ovoj stanici.

Vertikalnu strukturu vjetra karakterizira maksimum brzine u gornjim slojevima troposefere 13. 4. dok u periodu sa jakom burom taj maksimum opažamo unutar sloja NE strujanja na visini 500-1000 m. Posljedica ovakve strukture je izrazito vertikalno smicanje brzine unutar sloja bure (definiranog smjerom vjetra 15^{o} - 105^{o}), čija debljina varira između 1 km (na početku i kraju bure) i 2.5 km (za vrijeme najjače bure).

Analiza avionskih podataka za 15. 4. (Smith, 1987), kao i vertikalne strukture stabilnosti atmosfere u navjetrini i zavjetrini ukazuju na razdvajanje kritičke strujnice iznad prepreke i njezino spuštanje prema moru. Kritička strujnica odvaja područje turbulentnog strujanja u sloju bure od neporemećenog strujanja u gornjim slojevima troposfere. Na pretpostavci razdvajanja navjetrinske strujnice, uzimajući kontinuirano stratificiranu atmosferu, Smith (1985) je razvio hidrauličku teoriju koja objašnjava dinamičke karakteristike olujnog vjetra niz planinu. U kasnijem radu Smith i Sun (1987) poboljšavaju teoriju uvođenjem stratificiranog dvoslojnog strujanja preko prepreke i dobivaju zadovoljavajuće slaganje između teorije i situacija s burom u ALPEX-SOP.

Uz pretpostavku konstantnog strujanja u navjetrini primjenjena je hidraulička teorija na odabrane periode s burom (13, 14 i 15. 4. u 12 GMT). Vertikalna struktura stabilnosti u navjetrini u terminima sa najjačom burom karakterizira prizemni plitki neutralni sloj (500 m) sa slojem veće stabilnosti iznad njega. Ovakav vertikalni profil stabilnosti omogućio je dva pristupa u primjeni hidrauličke teorije. U prvom slučaju primijenili smo generaliziranu hidrauličku teoriju uvažavajući oba spomenuta sloja. Uz zanemarivanje prizemnog neutralnog sloja stabilnost postaje kontinuirana unutar sloja bure pa se hidrauličke jednadžbe svode na granični slučaj, Smith (1985). U oba slučaja teorija precjenjuje visinu kritičkog nivoa. Međutim, slične vrijednosti teoretskog i empiričkog Froudovog broja ukazuju da je pojava jake bure bila povezana prelaskom potkritičkog toka u superkritičko strujanje preko planine.

Na početku bure (13. 4) primjenom hidrauličke teorije koristeći jednadžbe Smitha (1985), teoretske vrijednosti

F_o znatno su manje od opaženih. Empirički dobiven F_o ukazuje na superkritičko strujanje iznad same prepreke i potkritičko u navjetrini i zavjetrini. Ovako nestacionarno stanje postat će stacionarno uspostavljanjem hidrauličkog skoka čija je posljedica i jača bura u kasnijim terminima.

Za razliku od 13. 4. generalizirana hidraulička teorija 15. 4, zanemarivanjem stabilnog sloja na visini, svodi se na jednoslojni model Longa (1954). Tada su dobivene slične vrijednosti hidrauličkih parametara kao kod Smitha (1987) i Smitha i Suna (1987). Time se pokazuje da bi se pomoću stacionarnih hidrauličkih jednadžbi mogla procijeniti visina razdvajanja kritičke strujnice.

Budući da hidraulička teorija pretpostavlja stacionarno strujanje tokom jedne situacije s burom, za očekivati je da će se bolji rezultati dobiti ako se osrednje svi raspoloživi vertikalni profili vjetra i stabilnosti u razdoblju 13-15. 4. Koristeći tako srednje stanje, donja troposfera je kontinuirano stratificirana sa malim vertikalnim smicanjem vjetra u sloju bure. Procijenjene i empiričke vrijednosti visine kritičkog nivoa i F_o su vrlo bliske. Međutim, pri navedenom proračunu vrijednost efektivne visine prepreke [h = hN/U] bila je veća od 1, što je teoretski navjeća vrijednost za h u modelu Smitha (1985). Da bi bilo h = 1 kod promatranih uvjeta bure, maksimalna visina prepreke trebala bi iznositi samo 500 m. Iz toga slijedi da je prema hidrauličkoj teoriji prelaz zraka na zavjetrinsku stranu moguć samo preko prepreka nižih od 500 m, potvrda čega je i dulje trajanje bure u Senju. Na uspješnost primjene hidrauličke teorije na prosječno stanje atmosfere u promatranoj situaciji ukazuje i procijenjena vrijednost bure 27.6 m s^{-1}, što je u skladu sa izmjerenim maksimalnim brzinama u Senju (28.4 m s^{-1}) i na Rijeka-aerodrom (31.4 m s^{-1}).

Vjerovatni uzrok primjećenih razlika između teoretskih i empiričkih vrijednosti hidrauličkih parametara je neuključivanje vertikalnog smicanja vjetra u profil NE strujanja u navjetrini bure i vlažnih procesa u određivanju stabilnosti atmosfere.